



Seismic hazard in Northern Algeria using spatially smoothed seismicity. Results for peak ground acceleration

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Abstract

Seismic hazard in terms of peak ground acceleration (PGA) has been evaluated in northern Algeria using spatially smoothed seismicity data. We present here a preliminary seismic zoning in northern Algeria as derived from the obtained results.

Initially, we have compiled an earthquake catalog of the region taking data from several agencies. Afterwards, we have delimited seismic areas where the b and m_{\max} parameters are different. Finally, by applying the methodology proposed by Frankel [Seismol. Res. Lett. 66 (1995) 8], and using four complete and Poissonian seismicity models, we are able to compute the seismic hazard maps in terms of PGA with 39.3% and 10% probability of exceedance in 50 years.

A significant result of this work is the observation of mean PGA values of the order of 0.20 and 0.45 g, for return periods of 100 and 475 years, respectively, in the central area of the Tell Atlas.

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1. Introduction

Northern Algeria has been the site of numerous historical earthquakes, and was therefore subject to extensive damage and several thousands of casualties in the past. Earthquakes up to magnitude $M_S = 7.3$ have been recorded in the Ibero–Maghrebian region during

this last century, such as the El Asnam earthquake of 10 October 1980. Other damaging earthquakes affecting northern Algeria are the Ain Temouchent earthquake of 22 December 1999 ($m_{bLg} = 5.7$) and the one in Beni Ourtilane of 10 November 2000 ($m_{bLg} = 5.6$), indicating the importance of the seismic hazard assessment for this region. This can be used to improve not only the estimates of the quantified hazard available today, but also to provide a reliable seismic hazard zoning in northern Algeria.

The aim of this study is to evaluate the seismic hazard in northern Algeria in terms of (peak ground

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acceleration) PGA for different return periods, by using the new methodology proposed by Frankel (1995) and developed here with certain modifications (Peláez, 2000; Peláez and López Casado, 2002). This methodology combines both parametric and non-parametric (non-zoning) probabilistic methods. Seismic sources are used when considering zones where certain parameters may be considered homogeneous, as in parametric methods. On the other hand, occurred earthquakes are considered wherever they have taken place, as in non-parametric methods. The Frankel (1995) methodology is well adapted to model the seismicity that cannot be assigned to specific geologic structures, which is usually known as background seismicity.

In regions where detailed knowledge of the related seismotectonics is not available, or is too complex to establish, this methodology is very suitable (Frankel, 1995; Peláez and López Casado, 2002).

Using this new methodology, seismic hazard maps in terms of PGA for return periods of 100 and 475 years have been computed, corresponding to 39.3% and 10% probability of exceedance in 50 years, respectively. The results obtained are consistent not only with the recorded seismicity during the last 300 years, but also with the tectonic features in the region.

2. Tectonic and seismotectonic setting

The area under study, northern Algeria, can be briefly described by including from north to south the following main structural domains: the Tell (Tell Atlas), the High Plateaus, the Sahara Atlas (Atlas Mountains system) and the Sahara Platform (Fig. 1). The tectonics of this region has been the subject of various studies, such as McKenzie (1972), Tapponier (1977), Meghraoui (1988), Aoudia and Meghraoui (1995), Mickus and Jallouli (1999) and Frizon de Lamotte et al. (2000). To the point, the Tell is part of an Alpine orogen that includes the Spanish Betic Mountains in the west and the Italian Apennines in the east. These Tell mountains consist of a succession of valleys (alluvial basins) and ridges formed by thrusts and folds with an E–W to NE–SW trending parallel to the coastline. The main transport direction of the thrust is S and SE. The High Plateaus zone is situated between the Middle Atlas, the Tell and the Sahara Atlas, in an elevated region of relatively tabular topography characterized by a thin Meso–Cenozoic cover. The Sahara Atlas belongs to the Atlas Mountains system (Anti, High and Middle Atlas in Morocco, Sahara Atlas in western Algeria, Aurès in eastern Algeria and Tunisian Atlas in Tunisia), a mountain range with a deformed faulted and folded Mesozoic–

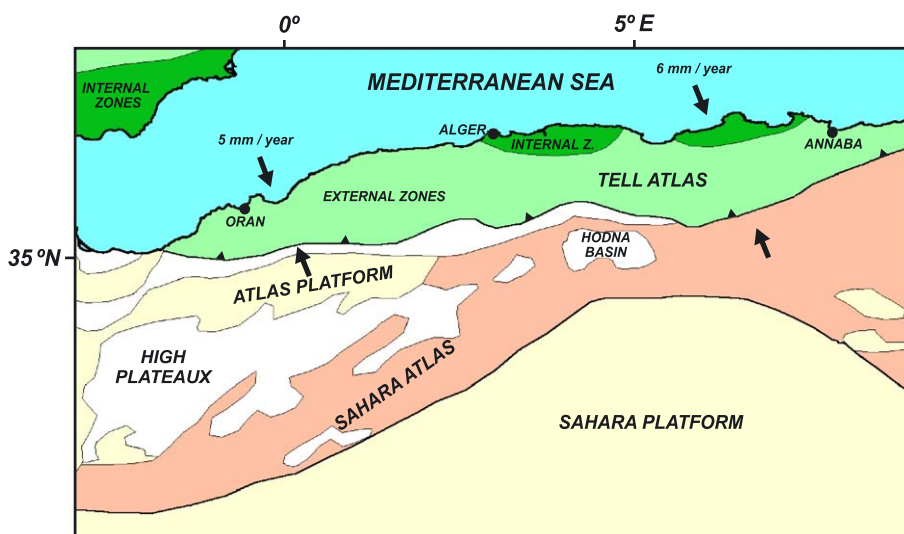


Fig. 1. Schematic map showing the main tectonic and geologic domains in northern Algeria (modified from Frizon de Lamotte et al., 2000).

Cenozoic cover. The Sahara Platform is characterized by no important Meso–Cenozoic deformations. It represents the southern limit of the studied area.

The Tell is the eastern part of the Rif–Tell system, an active collision area between the Spain microplate and the Africa and Europe plates, composed of, as in the case of the Betic mountains, internal and external zones with different seismic characteristics. Since the early Cenozoic, this area is under a compressional regime, with a N–S to NW–SE convergence from the late Quaternary. Post-nappes basins present E–W to

NE–SW folds and reverse faults. According to Meghraoui (1988), Bezzeghoud and Buform (1999) and Henares et al. (2003), this active zone absorbs 4–6 mm/year (from the Nuvel-1 model of Argus et al., 1989) of crustal shortening, with predominant dextral shearing, and it is responsible of the present seismicity. The main faults, with strike NE–SW, correspond to thrust faults dipping to NW often organized in echelon systems, such as the El Asnam and Tipaza faults (Bezzeghoud and Buform, 1999; Aoudia et al., 2000).

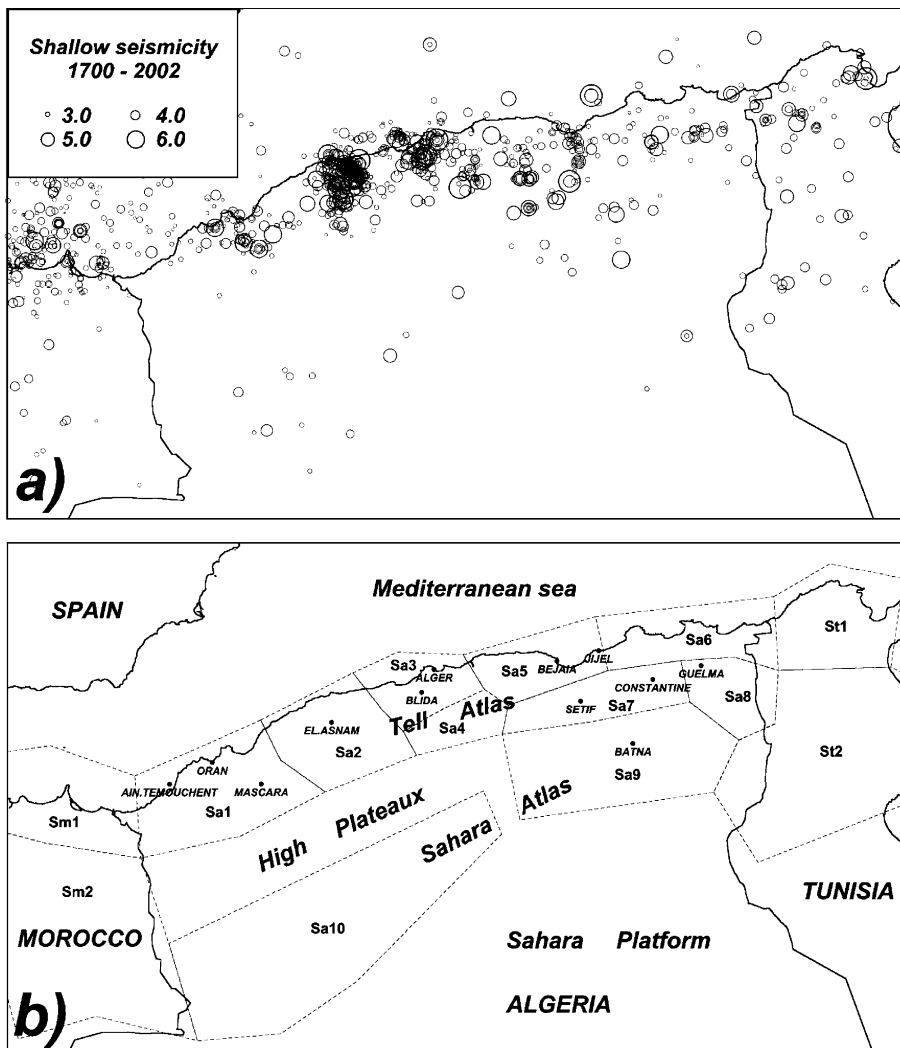


Fig. 2. Seismicity included in the compiled earthquake catalog and seismic sources (seismogenic and seismicity sources) used to evaluate the seismic hazard in northern Algeria region.

Northern Algeria is known as the most active seismogenic area in the western Mediterranean region, in the eastern part of the Ibero–Maghrebian zone. In fact, during the last century, Algeria has experienced several strong earthquakes (CRAAG - Centre de Recherche en Astronomie and Astrophysique et de Géophysique, 1994). The analysis of the distribution of earthquake epicenters during the last three centuries leads to the conclusion that earthquakes in Algeria occur mostly in some Tell cluster zones. However, a few earthquakes appeared in the High Plateaus and across the Sahara Atlas range (Fig. 2a).

According to Aoudia et al. (2000), the seismicity analysis also shows that the seismogenic areas are located in the vicinity of the Quaternary Basins. These tectonic zones, that coincide with the areas in which there are Neogene and Quaternary deposits, extend to the Messeta Basin (region of Oran) in the western Tell, in the center to the Mitidja Basin (Tipaza–Algiers) close to the Atlas blideen (or Blidean Atlas, from the Blida city), and extends to the Soumam, Constantine and Guelma Basins in the eastern part, and to the Hodna Basin in the southeast.

As in probabilistic parametric methods, we have used a delimitation in seismogenic source zones. Yet, in the absence of both a standard general practice and methodology, the delineation of the seismic sources remains mostly subjective. In this study, seismogenic source zones are defined as areas where the seismic characteristics are as homogenous as possible—that is, we have established a homogeneous (representative of the whole zone) earthquake recurrence relationship. In this work, some modifications were introduced into the seismogenic source zones previously proposed by Hamdache (1998a) and Aoudia et al. (2000).

The geological description given in Aoudia et al. (2000) was also used to incorporate the geological knowledge in the seismogenic sources considered in this study. Different geological structures have been included to identify overall 10 seismogenic zones in northern Algeria (Fig. 2b). Each of the proposed source zones, which seem homogeneous in their seismic characteristics, is often related to active or potentially active geological structures. Some of them contain the Quaternary basins previously mentioned. This seismogenic source model is consistent with the distribution of the seismicity in northern Algeria, as shown in Fig. 2a. In northeastern Morocco and

northern Tunisia, the source zones have been defined further, taking into account the seismicity information more than the geological context (seismicity sources). This was carried out to incorporate the contribution of the seismicity of these regions in the calculation of the seismic hazard in northern Algeria.

3. Data used

The earthquake catalog compiled for this study mainly consists of those published by the Spanish Instituto Geográfico Nacional (IGN) (Mezcua and Martínez Solares, 1983), supplemented for the Algeria zone with data published by the Centre de Recherche en Astronomie and Astrophysique et de Géophysique (CRAAG, 1994) and updated to 2002. The data published for the region by the European–Mediterranean Seismological Centre (EMSC) and by the US Geological Survey (USGS) have also been incorporated into the data file. All the magnitudes and intensities were converted to M_S magnitudes using the relationships by López Casado et al. (2000), and all the non-Poissonian earthquakes identified via the methodology proposed by Electric Power Research Institute (EPRI, 1986) have been removed.

The relationship between I_0 and M_S used is the following

$$M_S = 1.52 + 0.051I_0^2 + 0.70P$$

and the one between m_b and M_S magnitudes is

$$M_S = -3.44 + 1.65m_b + 0.40P$$

In both cases, $P=0$ for mean values, and $P=1$ for 84-percentile values. These relationships (López Casado et al., 2000) have been specifically computed for the Ibero–Maghrebian region.

The completeness of the final catalog has been verified according to the procedure developed by Stepp (1971). This check is a key step to establish the seismic models to be used in the calculation of the seismic hazard. The Poissonian character of the final catalog has been analyzed by considering the cumulative earthquake number as a function of time above different magnitude values (Benjamin and Cornell, 1970).

Our earthquake catalog could be improved in the future, but we believe that it already provides us with a very good reference frame for the calculation, using the spatially smoothed seismicity methodology, of the seismic hazard in the studied area. Although it would be desirable to have a longer span of the catalog, we can state that it covers the average recurrence time of the El Asnam fault for large earthquakes ($M > 7$). In their comprehensive study on the paleoseismicity of this fault, Meghraoui and Doumaz (1996) found three palaeoearthquakes in the last 1000 years using earthquake-induced flood deposits. They consider that the last 1000 years is an epoch of high seismic activity in comparison with previous ones.

The delimitation of seismic sources is shown in Fig. 2b. Concerning northern Algeria, as explained previously, the delimitation of seismogenic sources is based on that proposed by Hamdache (1998a), allowing for certain modifications according to the model of Aoudia et al. (2000). In all sources, only the shallow seismicity ($h < 30$ km) has been used.

Each of the proposed seismic zones has been characterized by their respective b and m_{\max} parameters of the truncated Gutenberg–Richter relationship (Cosentino et al., 1977). In order to do so, the procedure developed by Weichert (1980) was applied to derive a reliable estimate of the b value, and the one developed by Pisarenko et al. (1996) for the calculation of the expected m_{\max} value. In the computation of the uncertainty of this last parameter, we combine the sample standard deviation provided by the statistical method by Pisarenko et al. (1996), in all cases below 0.2 units, and the uncertainty of earthquake magnitude (Tinti and Mulargia, 1985). We consider, as a conservative decision, that for the whole catalog the uncertainty in the magnitude is, on average, 0.3 units after 1980, 0.5 between 1920 and 1980, and 0.7 before 1920 (Molina, 1998; Peláez, 2000).

The results obtained are shown in Table 1. The b values agree quite well with those previously obtained for different areas of the region by several authors in comprehensive studies (e.g., López Casado et al., 1995, 2000; Hamdache et al., 1998; Aoudia et al., 2000). Note that b values from M_S magnitude data are smaller than those obtained from the m_b data. The scant number of earthquakes in some source zones forces us to associate to these zones an average regional b value, as indicated in Table 1. Although

Table 1
 b and $M_{S_{\max}}$ values computed for the considered seismic sources

Seismic source	b, σ	$M_{S_{\max}}, \sigma$			
		Model 1	Model 2	Model 3	Model 4
Sa1	0.54, 0.06	6.5, 0.3	6.5, 0.3	6.5, 0.3	7.0, 0.7
Sa2	0.49, 0.07	7.8, 0.3	7.8, 0.3	7.8, 0.3	7.8, 0.3
Sa3	0.58, 0.08	6.2, 0.3	6.2, 0.3	6.5, 0.7	7.5, 0.7
Sa4	0.51, ^a 0.03	4.7, 0.5	5.6, 0.5	7.1, 0.7	7.1, 0.7
Sa5	0.62, 0.12	5.6, 0.3	5.6, 0.5	7.5, 0.7	7.5, 0.7
Sa6	0.51, ^a 0.03	6.1, 0.5	6.1, 0.5	6.1, 0.5	6.1, 0.5
Sa7	0.51, ^a 0.03	7.5, 0.5	7.5, 0.5	7.5, 0.5	7.5, 0.5
Sa8	0.56, 0.27	4.7, 0.5	5.7, 0.5	5.7, 0.5	5.7, 0.5
Sa9	0.51, ^a 0.03	6.8, 0.3	6.8, 0.3	6.8, 0.3	6.8, 0.3
Sa10	0.51, ^a 0.03	4.6, 0.5	5.5, 0.5	5.5, 0.5	5.5, 0.5
Sm1	0.58, 0.11	6.3, 0.3	6.5, 0.5	6.5, 0.5	6.5, 0.5
Sm2	0.58, 0.12	4.8, 0.3	5.5, 0.5	5.5, 0.5	5.5, 0.5
St1	0.58, ^b 0.09	6.0, 0.5	6.1, 0.5	6.1, 0.5	7.5, 0.7
St2	0.58, ^b 0.09	5.5, 0.3	5.5, 0.5	5.5, 0.5	5.5, 0.5

^a Mean value obtained using all the Algerian sources.

^b Mean value obtained using all the Tunisian sources.

in this methodology, it is not as critical as in the parametric approach, the b and m_{\max} values have been smoothed using the procedure of Bender (1986).

As noted before, we have only considered the shallow seismicity, with depths of less than 30 km. To avoid the insufficient information related to the depth of the events, a standard value of 5 km has been associated to all sources. This value results from averaging the scarce focal depth data in the studied region.

The attenuation relationship developed by Ambra-seys et al. (1996) has been used in this study. This relation is given by the expression

$$\log(\text{PGA}) = -1.39 + 0.266M_S - 0.922\log(r) + 0.25P$$

where

$$r^2 = d^2 + h_0^2$$

The term d is the shortest distance to the surface projection of the fault rupture, h_0 is a constant value equal to 3.5, and P is equal to 0 for mean PGA values, and equal to 1 for 84-percentile values.

Although it is developed for the European continent, the fact that the authors used accelerograms of seven earthquakes recorded at different stations in northern Algeria, led us to consider it as the most

reliable for this region and, hence, suitable for the purpose of our work. Among these seven earthquakes we can highlight the Tipaza earthquake of 29 October 1989 ($M_S=5.7$).

4. Seismic models and methodology

Four seismic models were used for the calculation of the seismic hazard in the studied area. All of them were obtained from the earthquake catalog compiled specifically for this work, each covering a different interval of time, and being complete and Poissonian.

4.1. Model 1

This model includes earthquakes with magnitude greater than or equal to $M_S=2.5$ ($\sim m_b$ 3.6, $I_0=IV-V$, according to the relationships by López Casado et al., 2000) after 1960. This model is the most complete from the spatial point of view—that is, this is the model which includes the largest number of earthquakes covering the largest area. An analysis of their Poissonian properties gives a constant annual rate of 9.4 earthquakes above the minimum magnitude cho-

sen. To incorporate this model into the seismic hazard analysis and taking into account the uncertainty in the earthquake location, the adopted value of the c parameter in the Gaussian filter (Frankel, 1995) is equal to 10 km. The model includes a total of 425 earthquakes (Fig. 3).

4.2. Model 2

This model includes earthquakes with magnitude greater than or equal to $M_S=3.5$ ($\sim m_b$ 4.2, $I_0=VI$) after 1920. An annual activity rate equal to 3.9 earthquakes is obtained for this model. The c parameter in the Gaussian filter is 15 km in this case. The total number of events included in this model is 313 (Fig. 3).

4.3. Model 3

This model includes earthquakes with magnitude greater than or equal to $M_S=5.5$ ($\sim m_b$ 5.4, $I_0=VIII-IX$) after 1850. An annual rate of 0.16 earthquakes has been obtained and a value of 20 km was adopted for the c parameter. The total number of events included in this model is 27 (Fig. 3).

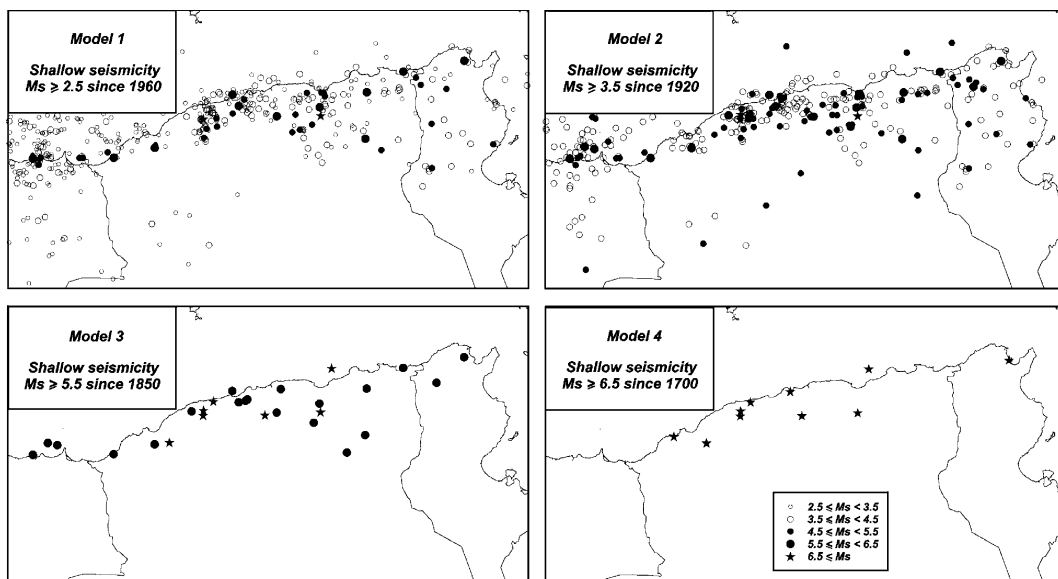


Fig. 3. Shallow seismicity included in the different models.

4.4. Model 4

This model includes earthquakes with magnitude greater than or equal to $M_S = 6.5$ ($\sim m_b$ 6.0, $I_0 = IX - X$) after 1700. Only 10 earthquakes are included in this last model. The obtained annual rate is 0.033. As

in the previous model, the c parameter was assumed to be 20 km. The epicentral distribution of earthquakes included in this fourth model is shown in Fig. 3.

The completeness and Poissonian character of our four seismic models is inferred from Fig. 4, showing how the annual rate is constant for those earthquakes

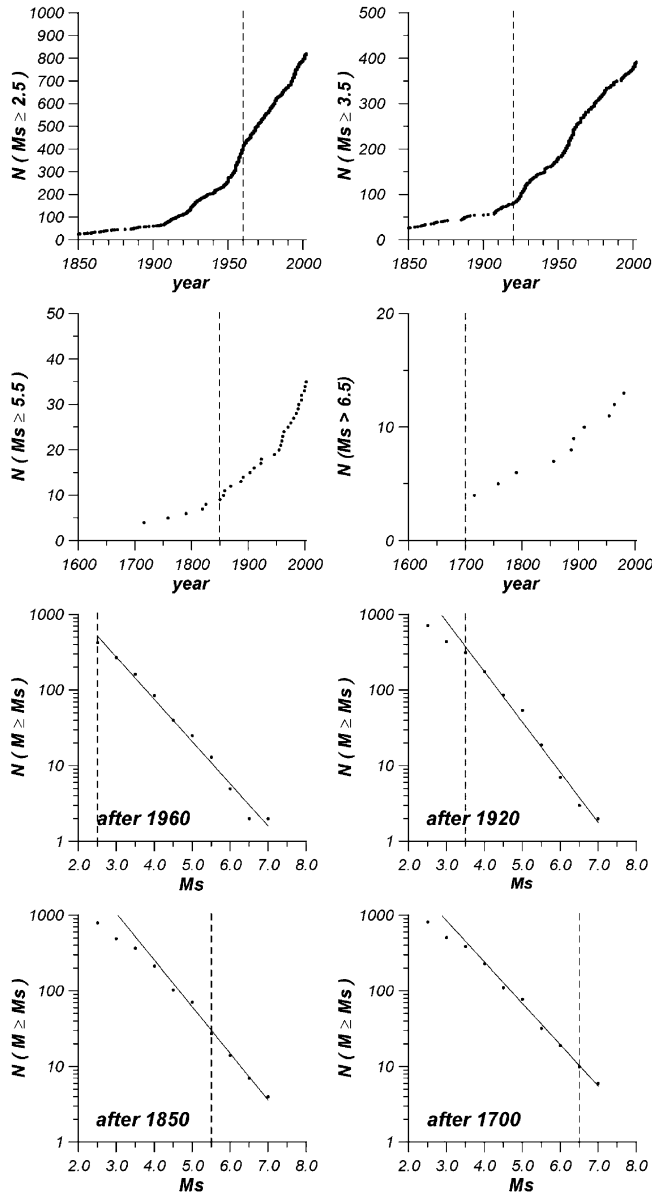


Fig. 4. Four uppermost plots: number of earthquakes above the threshold magnitude considered in each seismic model vs. time. Four bottom plots: accumulative number of earthquakes vs. magnitude. In all plots, the dashed line shows the threshold date or threshold magnitude considered in each seismic model.

considered in each model. Also, it is shown that earthquakes agree very well with a Gutenberg–Richter relationship for the dates and magnitude ranges taken into account in each seismic model.

It is important to point out that the seismicity included in the first two models (1 and 2) is the instrumental seismicity, with minimum uncertainty in their epicentral location. The last two models (3 and 4) include moderate and large earthquakes that have taken place in the region. Some of them are historical and thus, may have a high uncertainty, not only in their epicentral location but also in their intensity or macroseismic magnitude. These models are really necessary, because they reveal the areas tending to have high seismic hazard.

The methodology used in the assessment of the seismic hazard requires that the seismicity included in the models is complete. This requirement is due to the fact that the minimum magnitude chosen to calculate the hazard is $M_S = 2.5$, a value lower than the threshold magnitude of the models 2, 3 and 4. It has also been necessary to normalize the seismicity included in each of the four models in order to preserve the seismic activity rate. Model 2 has the highest annual rate above any magnitude, so that models 1, 3 and 4 have been normalized to it.

The procedure of the seismic hazard calculation is the usual one in the spatially smoothed seismicity methodology (i.e., Frankel, 1995; Lapajne et al., 1997; Peláez, 2000; Peláez and López Casado, 2002; Peláez et al., 2002). The area under study is first divided into square cells (10×10 km), then we count the number of earthquakes N recorded in each of them. Afterwards, we convert them to incremental values.

The Gaussian function (Frankel, 1995) was used to smooth the grid of N values, thus, including the uncertainty in the earthquake location in the seismic hazard results. One of the most important advantages of this function is the fact that it preserves the total number of earthquakes. Using this filter, the incremental N value in a given cell is obtained by averaging the values in the surrounding cells, the value in each of them contributes with a weight equal to

$$\exp(-(d/c)^2)$$

where d is the distance between two cells and c is a parameter of the filter (correlation distance). The

average takes into account only cells within a distance less than $3c$ from the one being considered. Therefore, $3c$ gives an estimate of the epicentral location in each seismic model.

The fraction q of earthquakes in the interval of magnitude $m \pm \Delta m/2$ is given by the expression (Peláez and López Casado, 2002)

$$q(m, \Delta m) = N \frac{10^{-b(m-m_0)}}{1 - 10^{-b(m_{\max}-m_0)}} \left[10^{b\frac{\Delta m}{2}} - 10^{-b\frac{\Delta m}{2}} \right]$$

where, as has been explained before, the truncated Gutenberg–Richter relationship has been used (Cosentino et al., 1977). The b , m_0 and m_{\max} parameters characterize the adopted recurrence model, Δm is the magnitude interval in the computation of the seismic hazard, and N is the total number of earthquakes in a given cell.

The calculation methodology to evaluate the seismic hazard is based on the well-known total probability theorem, expressed in terms of rate of exceedance of a certain level of ground motion. The final results are obtained by weighting the output of each of the four models. For the calculation of the seismic hazard with 39.3% probability of exceedance in 50 years, which corresponds to a return period of 100 years, the weights used are 0.2, 0.3, 0.3 and 0.2 for models 1, 2, 3 and 4, respectively. In estimating the seismic hazard with 10% probability of exceedance in 50 years, corresponding to a return period of 475 years, the respective weights are 0.2, 0.2, 0.3 and 0.3.

In both cases, the weighted values are proposed according to the return period. The models extending during an interval comparable to the return period provide a stronger contribution.

5. Results

The obtained results in this study are presented as PGA contour maps with 39.3% and 10% probability of exceedance in 50 years. The mean and worst cases are also shown. In the worst case map, the maximum seismic hazard generated in each location by any of the models is displayed, which represents the most “conservative” result obtained by using this methodology.

Table 2
Mean PGA values for 100 and 475 years of return period for 12 selected cities. The mean and worst case are shown

Cities	PGA (g)			
	100 years		475 years	
	Mean case	Worst case	Mean case	Worst case
El Asnam	0.181	0.189	0.393	0.460
Setif	0.102	0.120	0.223	0.247
Blida	0.118	0.134	0.219	0.255
Algiers	0.087	0.109	0.164	0.197
Mascara	0.074	0.087	0.159	0.185
Oran	0.068	0.095	0.138	0.180
Constantine	0.062	0.085	0.137	0.191
Guelma	0.071	0.105	0.120	0.190
Batna	0.060	0.078	0.118	0.157
Bejaia	0.071	0.087	0.117	0.144
Jijel	0.055	0.059	0.095	0.106
Ain Temouchent	0.049	0.063	0.094	0.114

The seismic model that embraces a wider time span includes the most energetic earthquakes in the last 300 years. Therefore, using only seismicity data we cannot provide reliable results for return periods greater than 475 years.

Fig. 4 illustrates the seismic hazard curves evaluated at five selected cities in northern Algeria, as an example: El Asnam, which could be considered as a place with high seismic hazard, and the cities of Setif, Algiers, Oran and Jijel, with moderate seismic hazard.

Table 2 shows the seismic hazard results obtained for 12 selected cities, located at the most industrial and populated areas in northern Algeria. The maximum PGA values are expected at the El Asnam city. Here, we obtained 0.181 g (~ VIII) and 0.393 g (~ IX) for the mean case and for return periods of 100 and 475 years, respectively. In the worst case, the maximum expected PGA values are of the order 0.189 g (~ VIII) and 0.460 g (~ IX–X), for the same return periods. The intensity values were obtained by using the relationship among the PGA and the macroseismic intensity proposed by *Murphy and O'Brien (1977)*, just as a reference. It is important to point out that similar results are expected in the worst and mean cases, indicating that the different seismic models used by us are appropriate and reliable: similar PGA values has been derived with each of them, especially in the areas with high level of seismic hazard. See also Fig. 5.

Figs. 6 and 7 show seismic hazard maps in terms of PGA for return periods of 100 and 475 years, respectively. For both of them, the mean and the worst cases are displayed, although the worst one cannot be considered a probabilistic result. According to this, the dominant characteristics in both figures are: (1) higher values of the seismic hazard in the central part of the Tell Atlas, which is

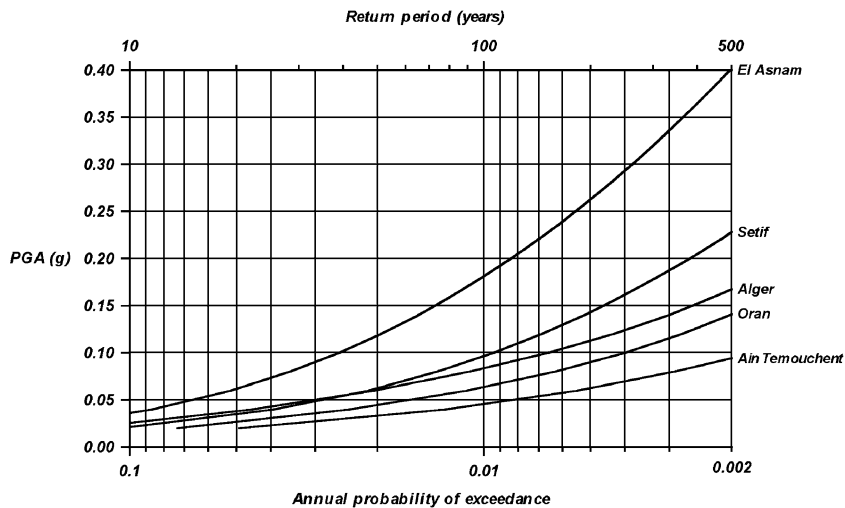


Fig. 5. Seismic hazard curves, showing different levels of seismic hazard, for five selected cities: El Asnam, Setif, Algiers, Oran and Ain Temouchent.

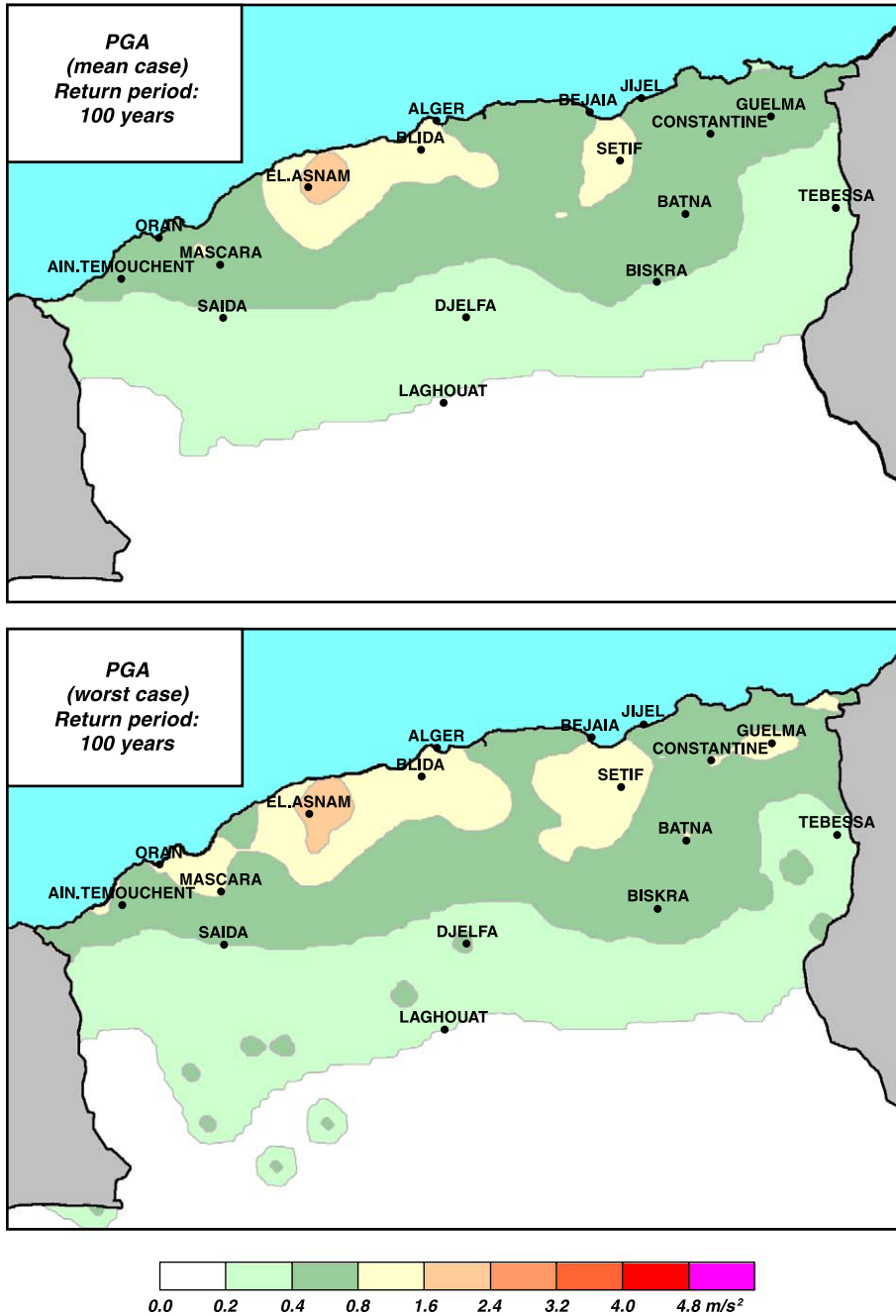


Fig. 6. Mean PGA with 39.3% probability of exceedance in 50 years (return period of 100 years). Top: mean value. Bottom: worst case.

the most seismic active area in the region, and (2) a gradual decrease of the seismic hazard to the south, toward the Sahara Atlas and the Sahara Platform.

For the return period of 100 years, values greater than 0.16 g are observed in the vicinity of the cities of Chlef (previously El Asnam) and Ain Defla, located at

the border of the Chelif Quaternary basin, one of the well-known and best-studied areas in the Tell Atlas (Meghraoui et al., 1986; Meghraoui, 1988; Yielding et al., 1989). This is a very active region, where several seismic events have occurred since the beginning of the 20th century. The same comments apply to the city of Tipaza, in the border of the Mitidja basin, on the coast, to the west of Algiers. A maximum PGA value of the order of 0.20 *g* is observed in the vicinity of some large historical earthquake locations, as the Dupleix earthquake, which took place on 15 January 1891 ($I_0=X$), and the El Asnam earthquakes of 9 September 1954 ($M_S=6.8$) and of 10 October 1980 (m_b 6.5, $M_S=7.3$). A relative maximum PGA value of the order of 0.11 *g* is observed near the city of Setif, located about 350 km from Algiers toward the east, in the border of the Hodna Quaternary basin. This domain is considered as a Neogene basin with relatively gentle topography, except where it is warped (or broken) into a series of ridges and valleys by folds and reverse faults trending E–W and NE–SW. The dominant geomorphology features of the Hodna zone consist of peneplain surfaces that are flat with internal drainage catchments, called Chotts. The region has experienced several destructive earthquakes, among them, the Bir Hadada earthquake of 4 September 1963 (m_b 6.3) and the M'Sila earthquake of 1 January 1965 ($M_S=5.5$).

For the return period of 475 years, the same pattern with the 100-year version is observed, but, as expected, with different levels. The greatest values of the expected PGA for this exposure time are found around the Chelif region, with a value close to 0.45 *g*. Near the city of Setif, it is of the order of 0.26 *g*.

In the maps showing the worst case, the El Asnam region stands out with maximum PGA values of 0.23 and 0.55 *g* for return periods of 100 and 475 years, respectively. The worst case maps are less smooth than the mean case, with typical “bull’s-eyes” generated by isolated epicenters.

6. Conclusion and discussion

In this study, the spatially smoothed seismicity methodology (Frankel, 1995) with modifications proposed by Peláez (2000) and Peláez and López Casado (2002) has been used to evaluate the seismic hazard in

northern Algeria. This methodology takes into account both the seismic characteristics and the different tectonic features of the studied area.

From the earthquake catalog, specially compiled for this work, containing both historical large earthquakes and more recent instrumental seismicity, four seismic models have been established to perform the calculation of the seismic hazard.

Our results are not only consistent with the tectonic features in the region but also with the size of the recorded seismicity during the last 300 years. Based on our work, northern Algeria appears as the most seismically hazardous area in the Ibero–Maghrebian region.

According to the obtained results in terms of PGA for a return period of 475 years, a preliminary seismic zonification in northern Algeria has been carried out (Fig. 8). The four levels defining this zonification are derived from the guidelines by Giardini et al. (1999). The area classified with very high seismic hazard, corresponding to a mean PGA, for a return period of 475 years, greater than 4 m/s² or 0.41 *g*, coincides with the locations of the 1954 and 1980 El Asnam earthquakes. This area embraces about 800 km². The high seismic hazard area (mean PGA greater than 2.4 m/s², or 0.24 *g*, for a return period of 475 years) is around the Chlef province, including the previous very high seismic area, as well as part of the province of Setif, in the vicinity of the 1963 Bir Hadada earthquake.

Most of the Tell Atlas is included in an area with moderate seismic hazard (PGA greater than 0.8 m/s², or 0.08 *g*, for a return period of 475 years). This agrees with the observed seismicity during the last 300 years, which can be characterized as a continuous activity of moderate and low-magnitude earthquakes. If we look at Fig. 2, we can see that most of the seismic activity is concentrated and clustered along the Tell mountains.

To the south of the Tell Atlas, the High Plateaus and the Sahara Atlas are included in an area with low seismic hazard (mean PGA less than 0.8 m/s² for a return period of 475 years).

Despite some differences, the seismic hazard zonification discussed above is remarkably similar to the one used by the modern Algerian building code (RPA-99, 2000) in terms of seismicity. The areas with both very high and high seismic hazard agree well with

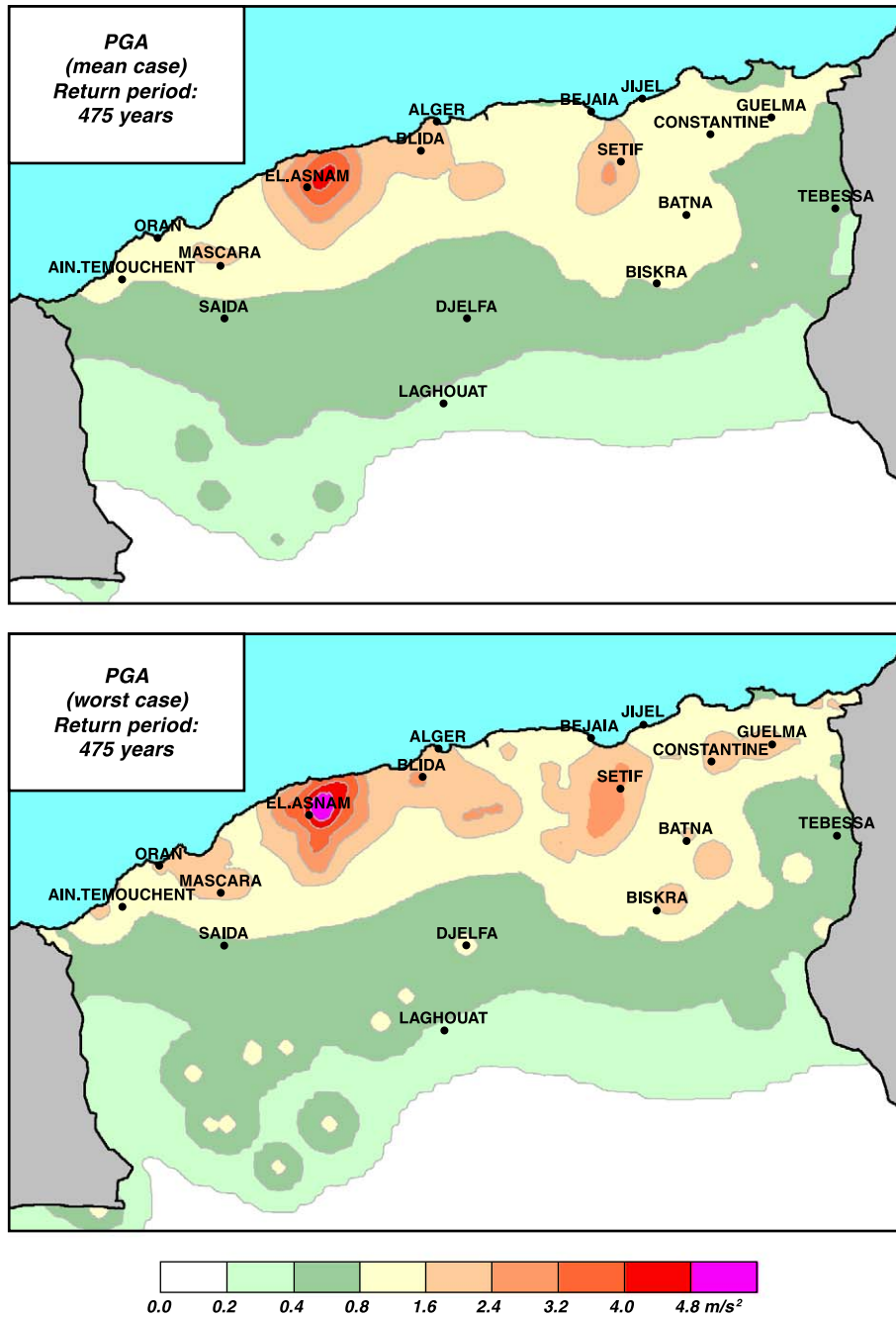


Fig. 7. Mean PGA with 10% probability of exceedance in 50 years (return period of 475 years). Top: mean value. Bottom: worst case.

those considered with high seismicity (zone III in the RPA-99). The area with moderate seismic hazard is consistent with the area of average seismicity (zone

II). Finally, the low seismic hazard area is also consistent with those of scarce (zone I) and negligible seismicity (zone 0).

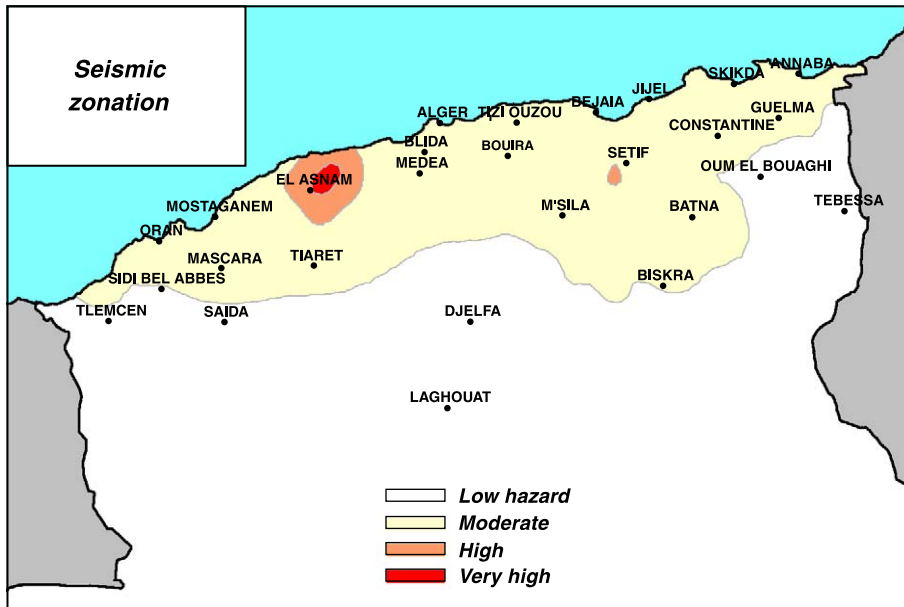


Fig. 8. Seismic zonation of northern Algeria in terms of the mean PGA values for a return period of 475 years: low hazard if $a < 0.8 \text{ m/s}^2$, moderate if $0.8 \leq a < 2.4 \text{ m/s}^2$, high if $2.4 \leq a < 4.0 \text{ m/s}^2$, and very high if $a \geq 4.0 \text{ m/s}^2$.

Using deterministic and probabilistic approaches, several attempts to compute seismic hazard in northern Algeria have been carried out by different authors. In Table 3, we compare our results with some of the main previous ones. Although it is not easy to improve a comparative analysis due heterogeneity reasons, some remarks can be pointed out.

Using non-zoning probabilistic methods, Hamdache (1998a,b) and Hamdache et al. (1998) computed

the seismic hazard not for sites, but for areas. The deterministic approach was used either to derive a seismic hazard map for the whole northern Algeria (Aoudia et al., 2000), or to carry out site-specific seismic hazard assessments in some places (Hamdache and Retief, 2001). Clearly, it is inadequate to make any comparison between these works and the probabilistic results reported in our study, although some careful comparison can be done concerning our worst case.

Table 3
Comparison between our mean PGA (g) results and those obtained by several authors at four selected test cities

	El Asnam	Algiers	Oran	Constantine
<i>Probabilistic results</i>				
This work, mean PGA 475 years	0.39	0.16	0.14	0.14
Naili and Benouar (2000), median PGA 475 years	–	0.25 to $>0.50^a$	–	–
Jiménez et al. (1999), mean PGA 475 years	0.33–0.41	0.16–0.24	0.08–0.16	0.16–0.24
Hamdache (1998a,b), mean PGA 390 years	0.19–0.34	0.11–0.22	0.13–0.23	0.11–0.24
Benouar et al. (1996), expected PGA 950 years	>0.31	0.20–0.31	>0.31	>0.31
Benouar (1996), median PGA 475 years	–	0.12	–	–
<i>Deterministic results</i>				
This work, mean PGA (worst case) 475 years	0.46	0.20	0.18	0.19
Hamdache and Retief (2001), maximum possible PGA	0.32	0.22	0.24	0.25
Aoudia et al. (2000), DGA ^b	0.4–0.6	0.1–0.2	0.1–0.2	<0.05

^a Depending on the used attenuation relationship.
^b Design ground acceleration using seismicity alone.

A non-zoning probabilistic method was also used by Benouar et al. (1996). Their seismic hazard maps in terms of PGA and macroseismic intensity for a return period of 950 years, corresponding to 10% probability of exceedance in 100 years, have been derived using an earthquake catalog that covers only the time period 1900–1990. In this work, different attenuation relationships have been tested, but the authors do not state which of their results is more reliable.

Parametric probabilistic methods have been used as well by some authors to perform seismic hazard maps in northern Algeria. The version proposed by Mortgat and Shah (1978), using the Bayesian probabilistic approach, is one of them. Using the same seismogenic source model with slight modifications, Jiménez et al. (1999) derived seismic hazard maps in northern Algeria in terms of PGA with 10% probability of exceedance in 50 years, by using the Cornell (1968) methodology and the computer code SEISRISK III (Bender and Perkins, 1987). As pointed out by the authors, the data that they used need a very crucial improvement. For example, the catalog used is not only heterogeneous, but also mostly incomplete.

We can state that all works that have been carried out so far mostly agree in the identification of which areas have the higher seismic hazard, although with different levels for the obtained PGA.

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